HIGH ENERGY ANODE MATERIAL DEVELOPMENT FOR LITHIUM-ION BATTERIES

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SiNode Systems, Inc.

DOE Annual Merit Review

June 7, 2017

ES240

Overview

Timeline

- Project start date: August 2014
- Project end date: July 2016
- Percent complete: 100%

Barriers

- Barriers addressed
  - Performance (energy, power)
  - Life (cycle and calendar)
  - Cost ($/kWh)

Budget

- Total project funding: $1M
- Funding received in FY16: $417k
- Funding for FY17: $0k

Partners

- Interactions/collaborations
  - Northwestern University: characterization
- Project lead
  - SiNode Systems

Relevance – Project objectives

- **Goal/Objective:**
  - Develop a high capacity Si-C based anode that can exceed DOE performance targets when paired with commercial cathode materials
  - Further optimize its manufacturability to meet commercially viable production protocols.

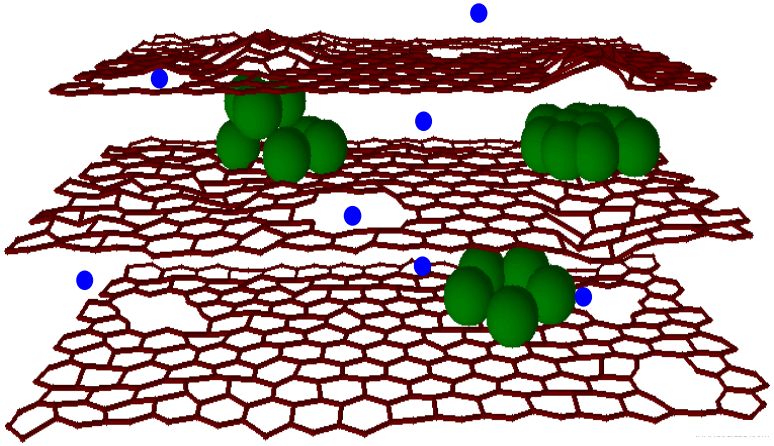
- **End performance targets:**
  - 200 Wh/kg cell energy, 1000 cycles
  - 750~1500 mAh/g anode, 1000 cycles

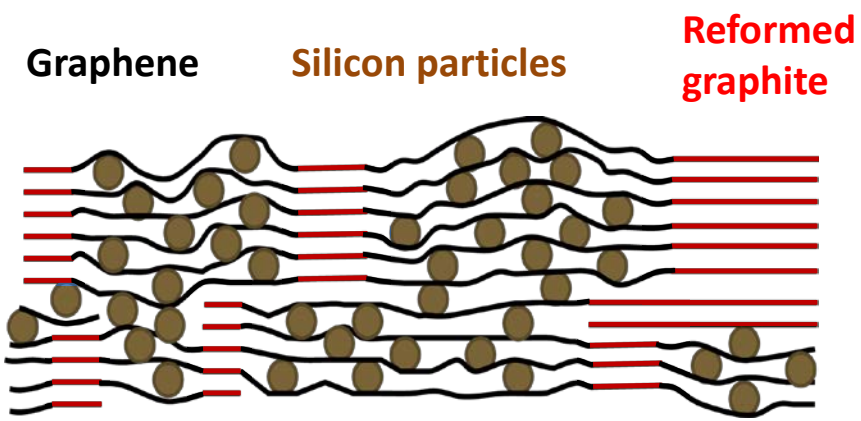
- **Year 2 Deliverables**
  - Cycling performance of a 1 Ah SiNode anode with high-energy cathode
  - Comprehensive report on current failure modes
  - Revised cost estimate on unit of SiNode material ($/kWh)
  - Roadmap to reduce costs to DOE target

Milestones (Phase II Year 2)

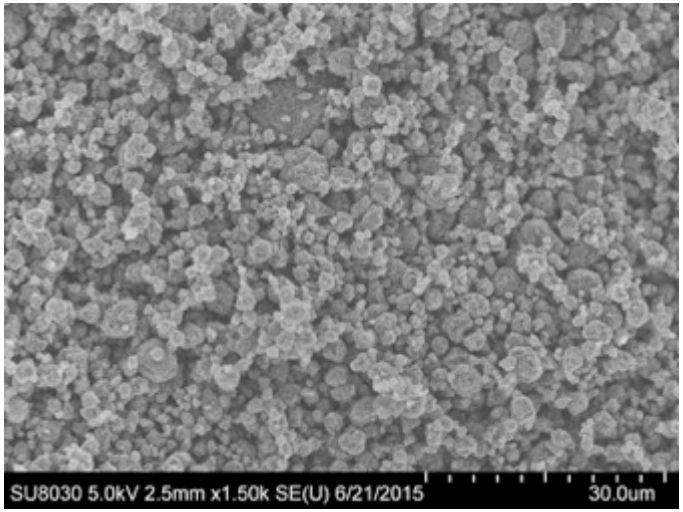
Date	Milestone	Status
November 2015	Complete transition to spray-dry processing technology	Complete
	Complete graphene structure modification results	Complete
	Increase solids content and loading	Complete
February 2016	Complete graphene oxide reduction effects analysis	Complete
	Identify improved electrolyte to increase energy and cycle life	Complete
	Design and build single-layer prototype cells	Complete
May 2016	Conduct pilot scale-up trials for powderization	Complete
	Complete analysis of scalable GO reduction methods	Complete
	Design and build updated prototype cells	Complete
August 2016 (Program Completion)	Complete pilot line design for industrial manufacturability	Complete
	Complete YR2 design and final cell build deliverable	Complete
	Finalize DOE Phase II testing report (w/ cost projections)	Complete

Approach: 3-D graphenic architecture





- ✓ Silicon particles wrapped in flexible, conductive graphene shell
- ✓ Engineered void space accommodates silicon expansion during lithiation
- ✓ Customizable micron sized particles
- ✓ Drop-in replacement for existing anode materials



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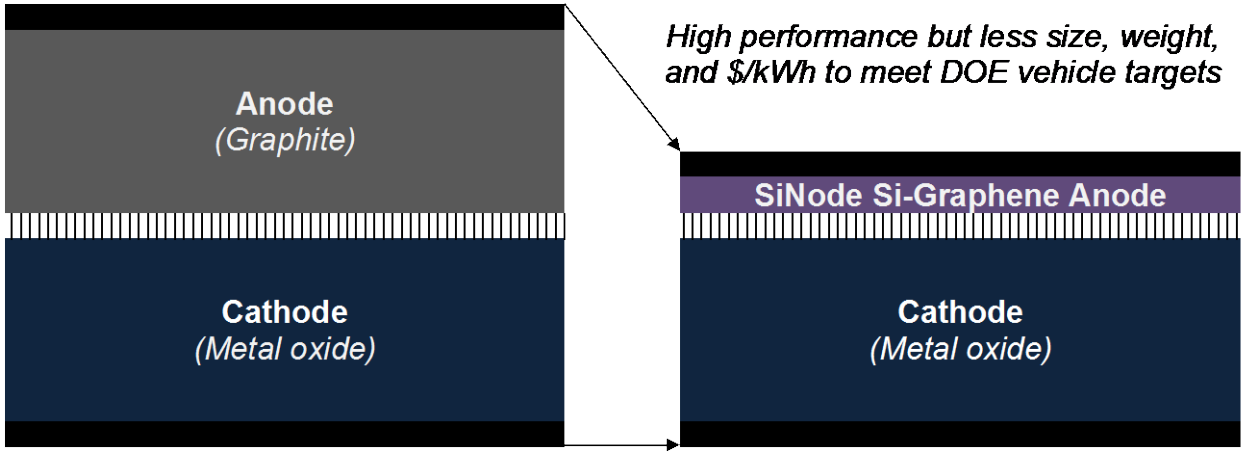
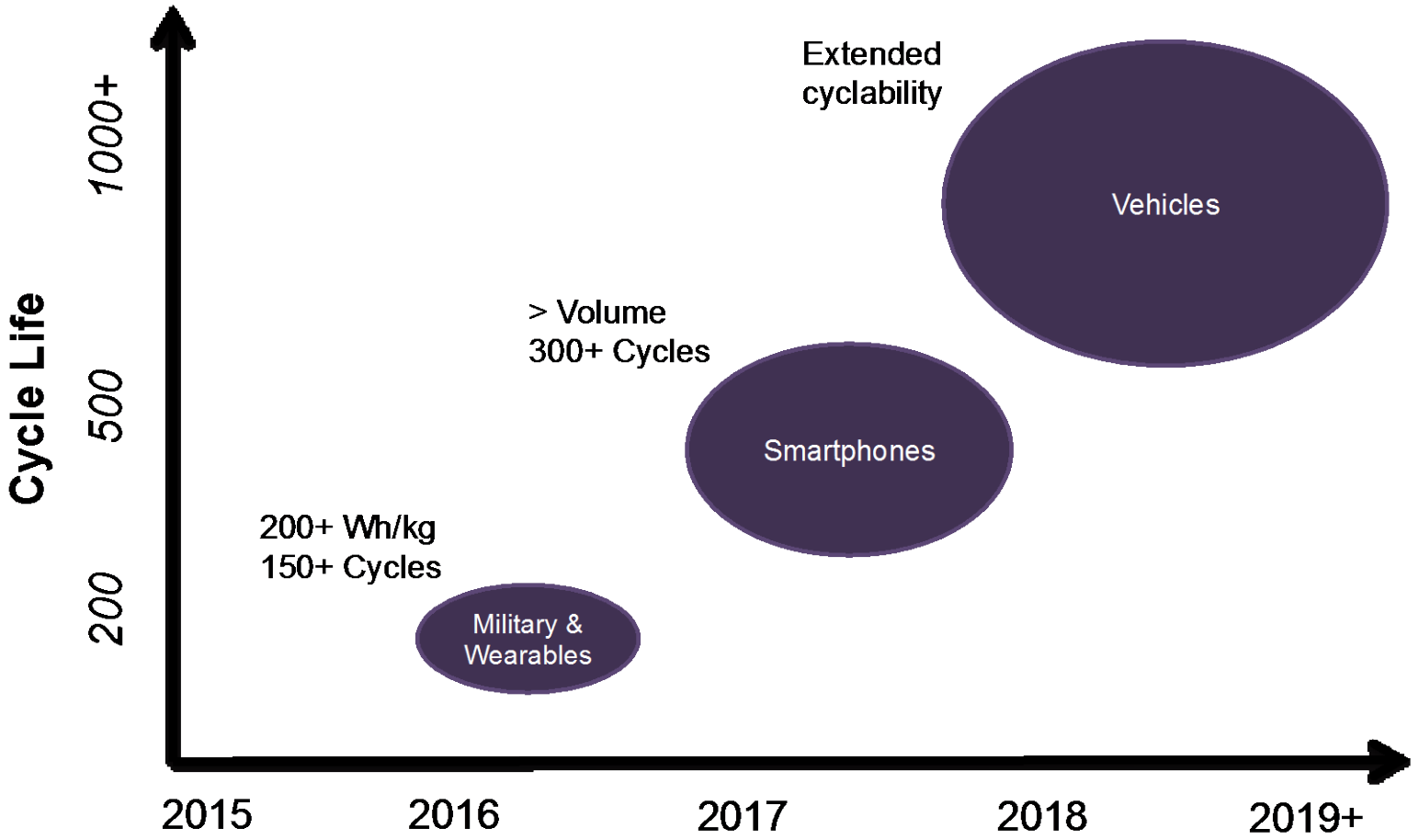
Approach: Value proposition



	Current Li-Ion Battery	SiNode Powered Battery
Cell Capacity	2 Ah	2 Ah
Anode Capacity	350 mAh/g	>2000 mAh/g
Anode Mass	6 g	1 g
Anode & Cathode Mass	17 g	12 g
Cost	$400-$500 / kWh	<$150 / kWh (Projected)

Approach: Staged market penetration



Production: Lab Prototypes → Pilot Scale → Large Scale

Funding: SBIR, Angels → SBIR, VC → Corporate Partner, PE

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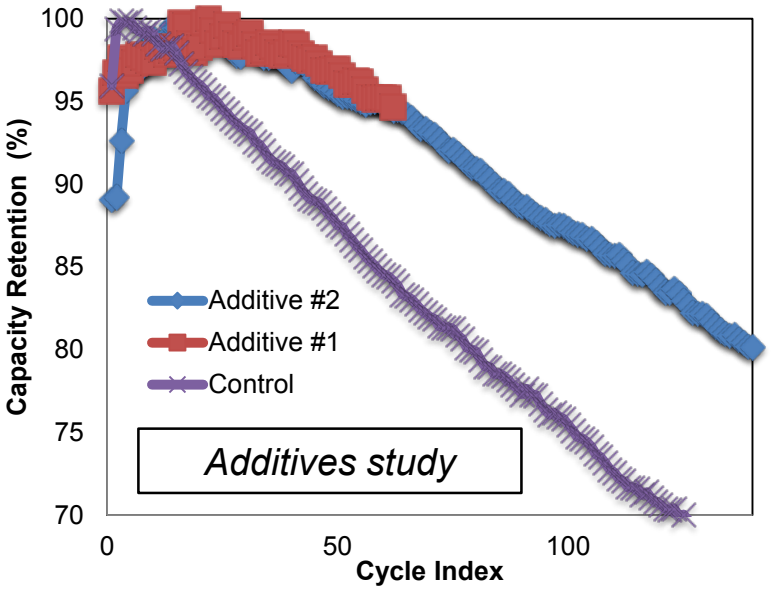
Technical Accomplishments: Overview

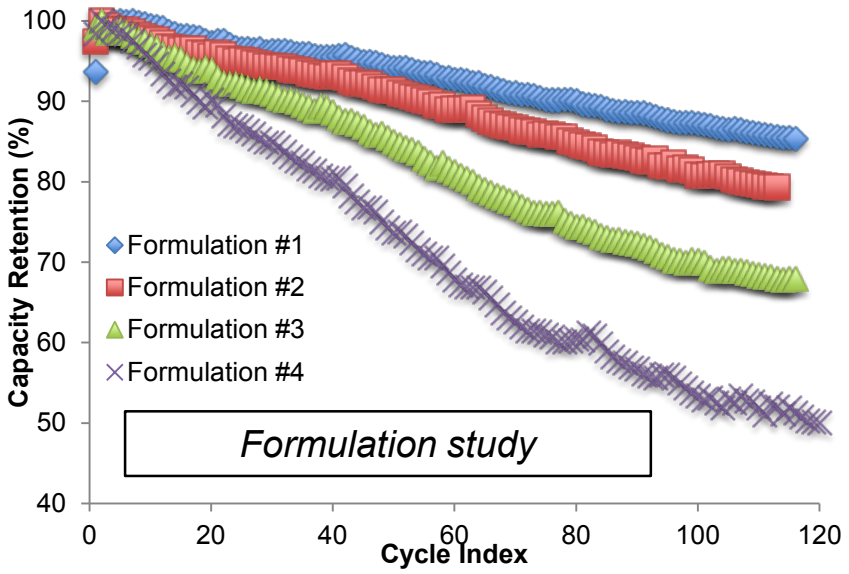
- ✓ Production process has scaled by 10,000X since program commencement without performance degradation
- ✓ Rational selection of silicon materials and design has extended cycle life by >100%
- ✓ Processing and formulation developments have further improved electrochemical characteristics (CE, specific capacity, surface area)
- ✓ Improved raw materials sourcing at low cost from multiple vendors has decreased costs by 10X and paved path to achieve USABC 2025 cost targets
- ✓ Prototype failure analysis has driven development of improved anode processing

Technical Progress: Previous accomplishments

Si-graphene system is responsive to formulation improvements to improve manufacturability and electrochemical performance

- Additives have been integrated into process to improve CE and cycle life
- Material formulation selection has significantly extended cycle life
- Scalable surface treatments improved cycle life and specific capacity values
- Optimizing material formulation and suppliers has decreased costs by >10X and increased scale



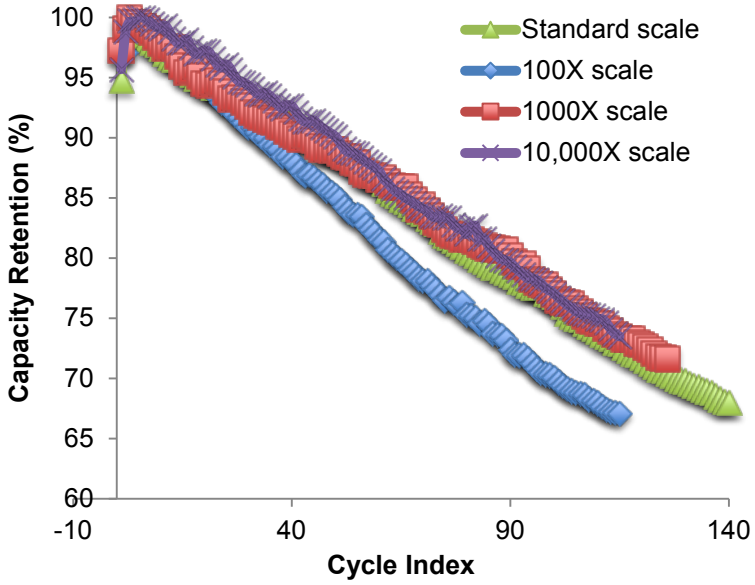


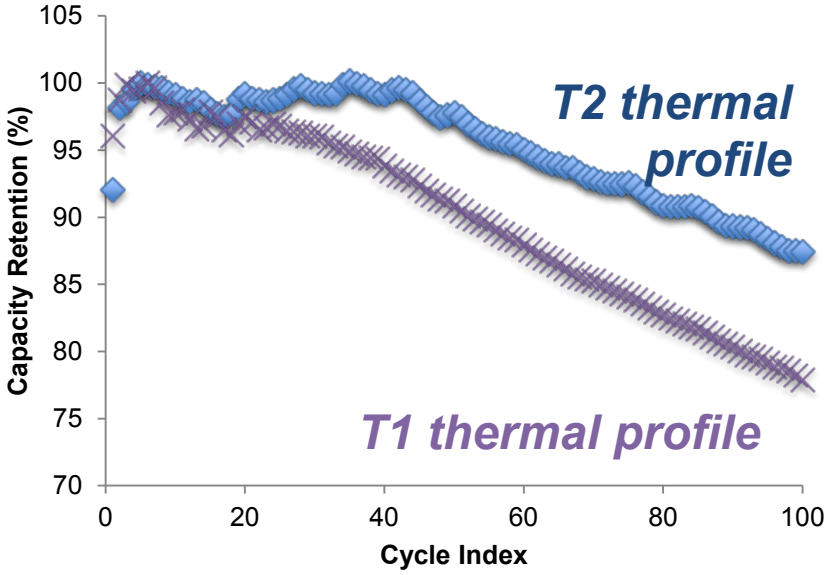
Cycling: 0.5C; 1.50-0.02V vs. Li/Li+

Technical Progress: Process improvements to extend cycle life

SiNode has further scaled up its production and thermal processing without impacting cycling performance

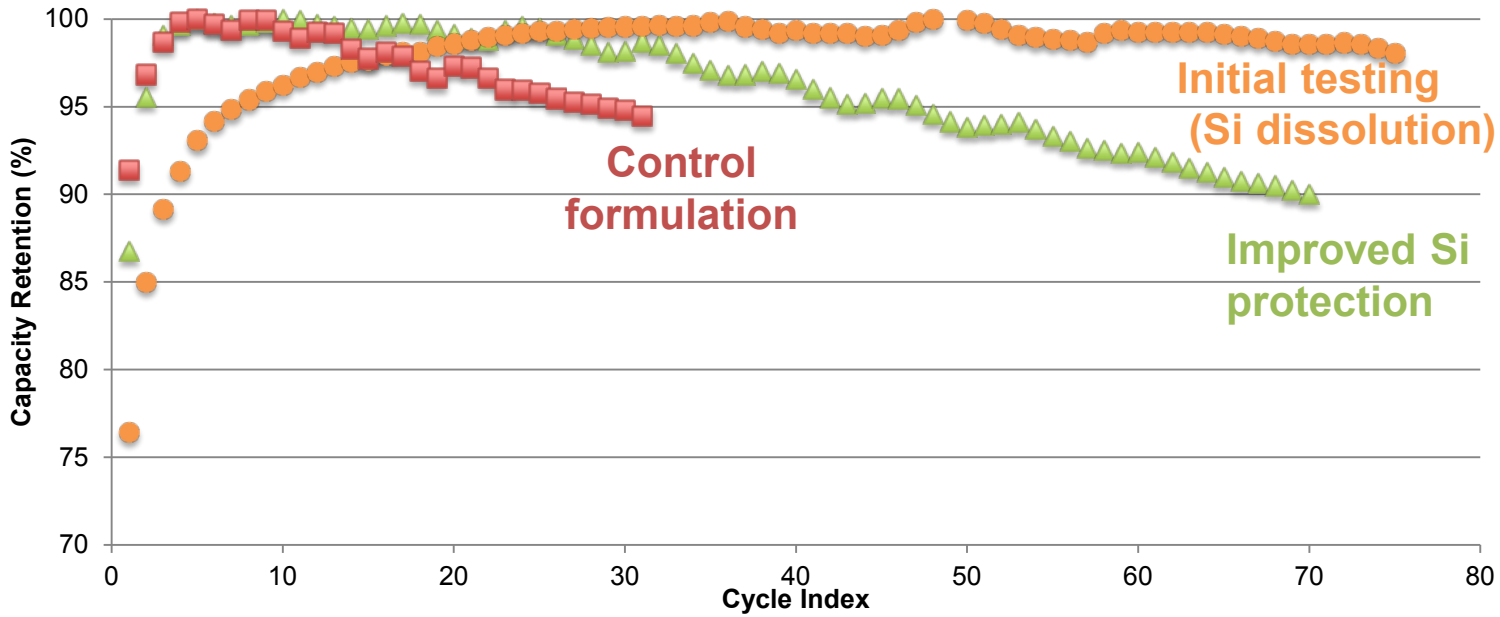
- 10,000X scale-up achieved since project inception
- Pathway to cost-effective industrial production scale has been identified
- Improved thermal processing procedure has increased cycle life by >67% and led to improvements in 1st Coulombic efficiency and cycling Coulombic efficiency





Cycling: 0.5C; 1.50-0.02V vs. Li/Li+

Technical Progress: Materials sourcing for cost reduction

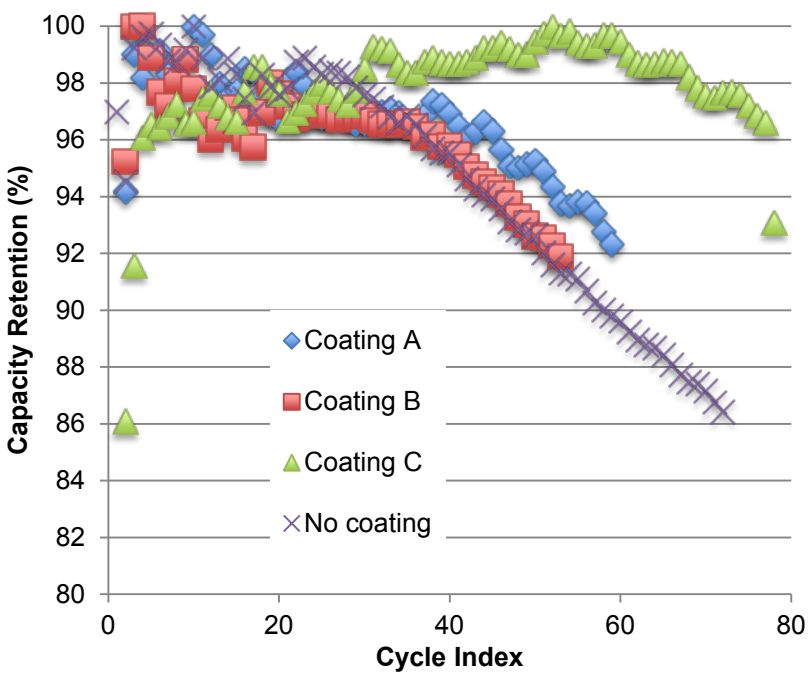


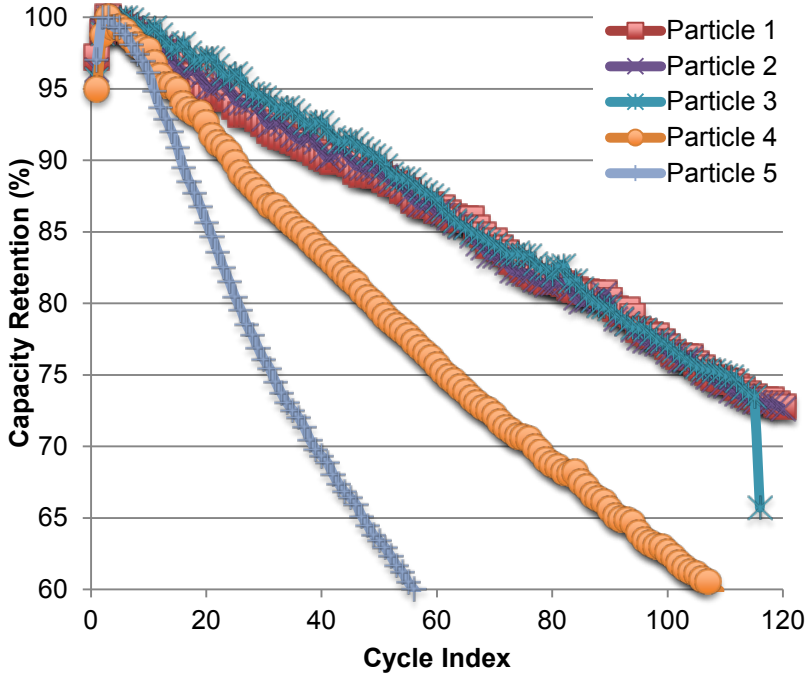
- Low-cost, large scale modified graphene material was investigated to decrease costs to achieve long-term cost targets
- Initial formulations show improved cyclability but low capacity due to particle etching
- Improved Si surface stabilization passivated the particle towards graphene stabilization agents and exhibited good cyclability

Modified graphene material offers attractive performance and inexpensive cost compared to control material

Cycling: 0.5C; 1.50-0.02V vs. Li/Li+

Technical Progress: Material development to extend cycle life



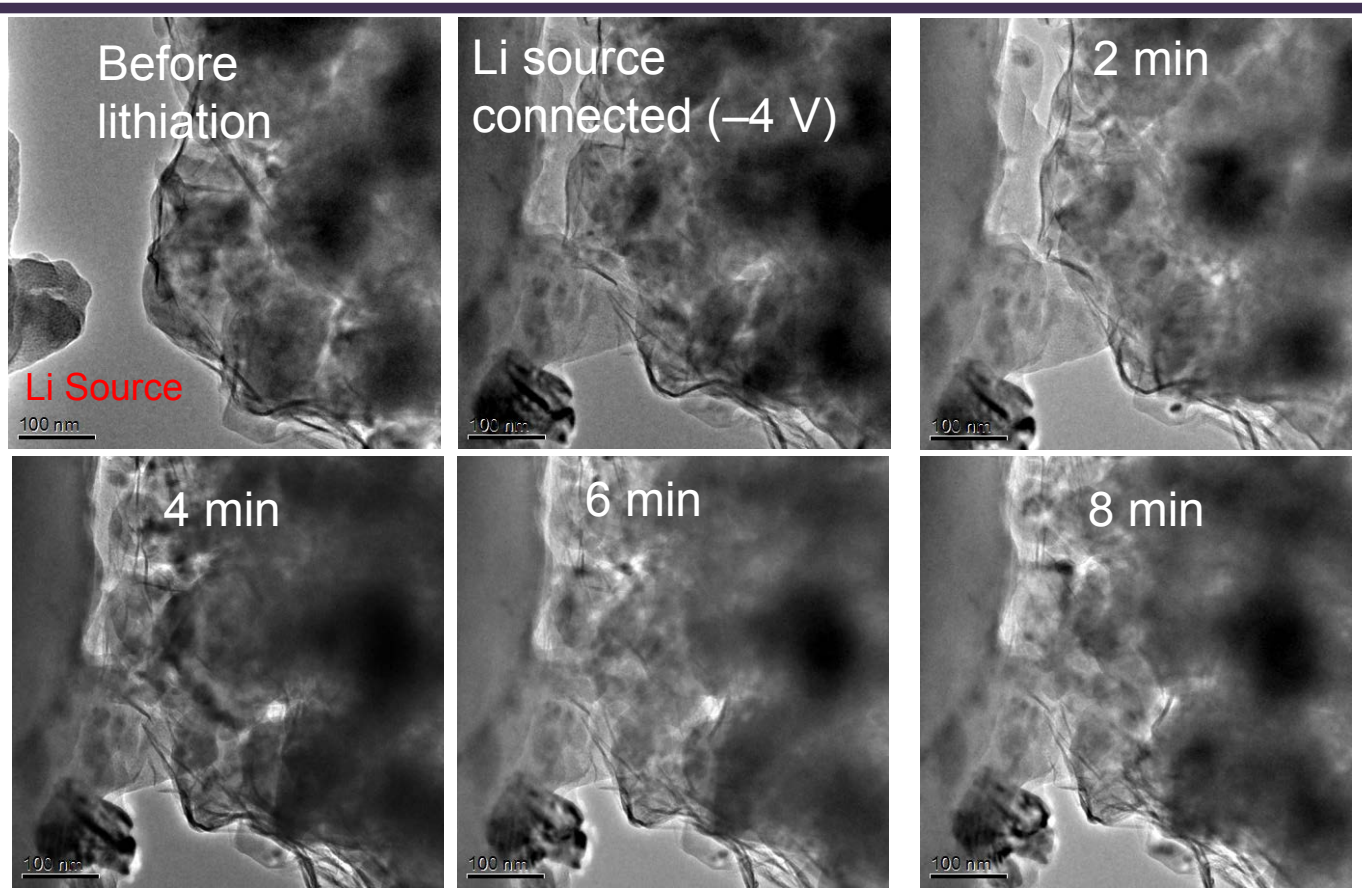


Optimized particles with improved barriers and surface protection are required to improve cyclability to achieve DOE/USABC cycling targets

- Proprietary surface coatings of various composition and thickness were investigated in order to promote improved SEI formation
- Surface coatings improved cycle life by >100% under certain conditions
- Particle size and density were tailored to provide extended cycle life

Cycling: 0.5C; 1.50-0.02V vs. Li/Li+

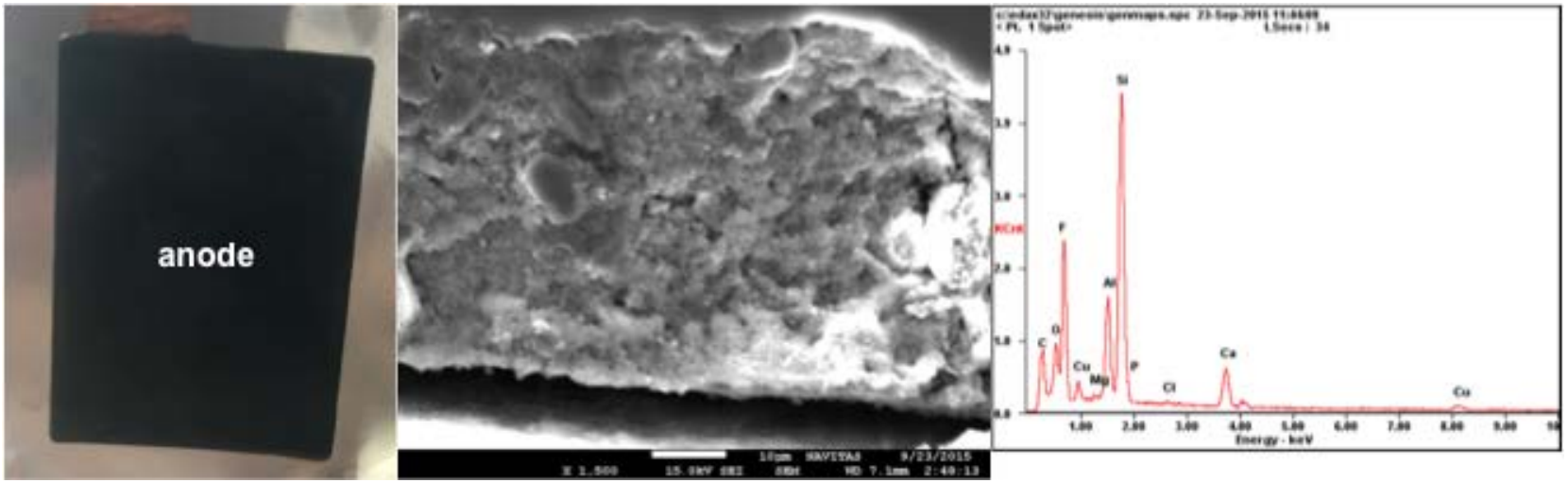
Technical Progress: In-situ TEM observations



- In-situ TEM observations showed that graphene shell successfully wrapped silicon particles during lithiation
- Void spaces accommodated silicon expansion during lithiation and buffered overall particle expansion

Courtesy: University of Illinois - Chicago

Technical Progress: Post-mortem analysis



- Electrode materials (pure Si-graphene as well as blends with graphite) exhibit good mechanical stability after cycling and only minor material loss
- SEI layer predominantly consists of C, F, O, and P elements
- Principle capacity fade mechanism is attributed to continual SEI growth on Si surface

Responses to Reviewer Comments

- ***Recommend collaboration with national laboratories for advanced characterization techniques***
  - SiNode has started additional collaborations with national labs and universities (including funded projects) to expand development via advanced characterization techniques.

- ***Develop collaborators to make cathodes….coat anode materials… and to manufacture finished cells.***
  - SiNode is working with industrial cell manufacturers with to develop high-energy finished cells.

Collaborators

Partner	Purpose
NORTHWESTERN UNIVERSITY	▪ Sample characterization ▪ Analytical work ▪ Materials treatments
MERCK	▪ Materials supply ▪ Assess manufacturing costs ▪ Sample characterization
UIC	▪ In-situ TEM characterization (external work)

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Remaining challenges & barriers

Performance characteristics & cycle/calendar life

- Prototypes with longer cycle life (>500 cycles) and high energy required for commercialization
- Current materials do not yet exceed DOE/USABC 2020 goals for commercialization

Cost

- Supply chain, active material formulation, and scale-up manufacturing required to achieve long-term cost targets

Safety testing

- Comprehensive safety testing on prototype cells required to determine characteristics

Proposed future work

- The project ended at the end of July 2016

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Summary

- ✓ SiNode is developing a Si-C anode that can exceed DOE performance targets when paired with conventional cathode materials
- ✓ Unique structure provides improved Si environment for extended cycling
- ✓ Materials sourcing, treatment, and processing steps have been examined in order to improve electrode cyclability
- ✓ Surface coatings and processing provides greatest opportunity for improvements
- ✓ Inexpensive raw materials can be easily integrated into existing processing

THANK YOU